Studies of Benioff-Zone Earthquakes Within the Anchorage, Alaska, Region

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Diane I. Doser
The University of Texas at El Paso
Department of Geological Sciences, 500 W. University Ave., El Paso, TX 79968
(915)-747-5851 (office), (915)-747-5073 (FAX), doser@geo.utep.edu,
http://www.geo.utep.edu/Faculty_Staff/doser.html
Element II
Seismology, source characteristics, seismotectonics

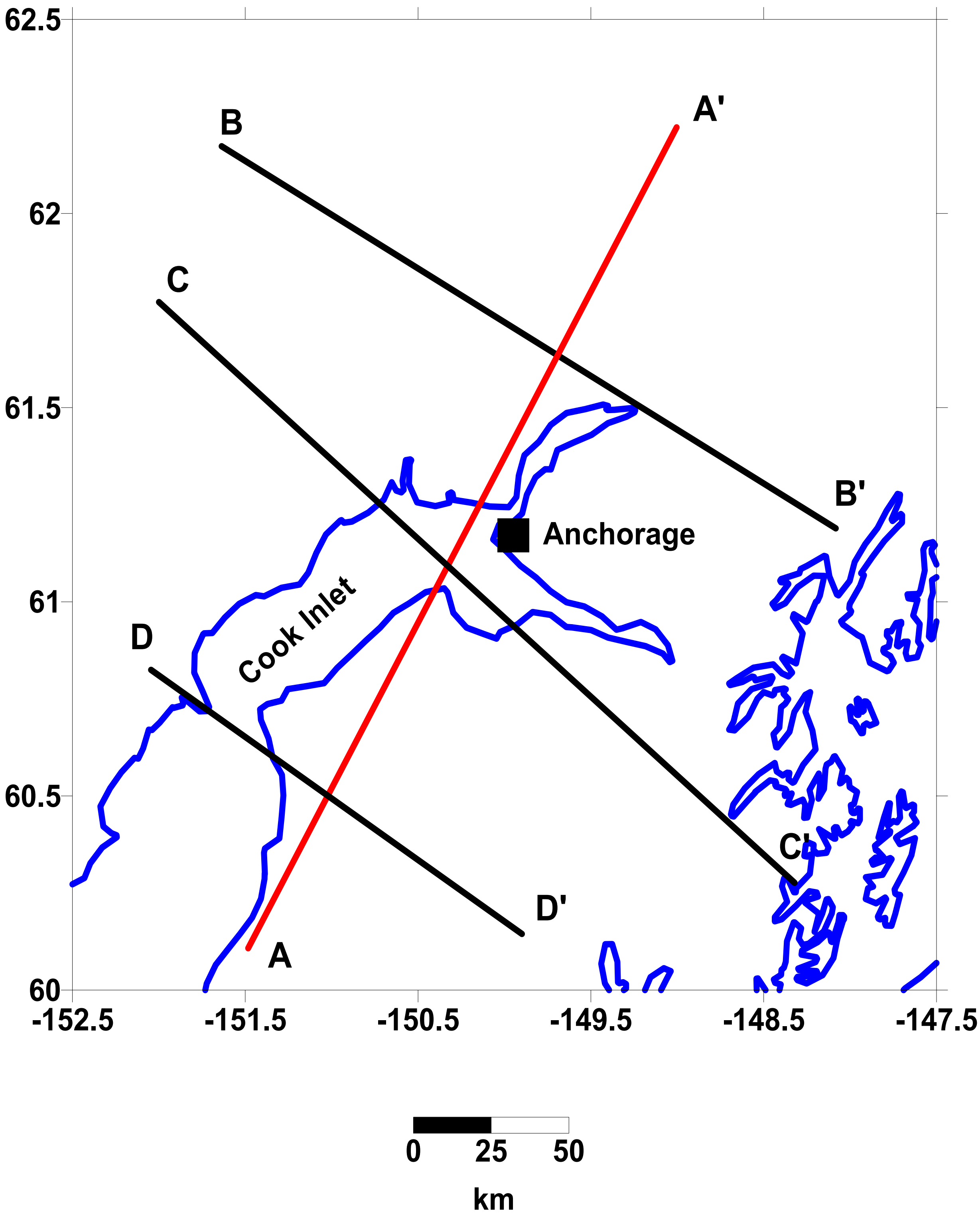
Investigations Undertaken:

The proposed research focuses on Benioff zone (lower plate) earthquakes of the Anchorage region (within ~150 km of Anchorage) (Figure 1). Benioff zone earthquakes represent one of two important seismic source zones for the Anchorage region. Historically, these earthquakes have produced significant damage (intensities of VII to VIII) within the Anchorage urban region. Since these lower plate earthquakes have smaller magnitudes than events along the plate interface, they may also be expected to have shorter repeat times. The research builds upon previous teleseismic waveform modeling and relocation studies of large (M_w>6.0), historic (1928-1964) earthquakes and moderate (M_w>5.7), recent, earthquakes (1964-1988) in both the upper and lower plates, as well as detailed relocation studies of upper plate seismicity (1971-2001) (Flores and Doser, 2004). The tasks to be accomplished for this study include: 1) detailed relocations of recent Benioff zone events (1964-present), 2) regional waveform modeling and empirical Greens function analysis of recent moderate (M_w>5.0) earthquakes (1988-present) to determine focal mechanisms, seismic moments, stress drops, focal depths and fault rupture processes, 3) teleseismic and regional waveform modeling of 5.7<m_b<6.3 Benioff zone earthquakes occurring up to 15 years prior to the 1964 mainshock, 4) examination of intensity data for historic and recent Benioff zone events to determine how these deeper events affect ground motion in the Anchorage region.

Ms. Annette Veilleux has worked as a research assistant on this project. She has completed relocation of Benioff zone earthquakes occurring within the Anchorage region between 1988 and 2000 using HypoDD (Waldhauser and Ellsworth, 2000) and presented results of her research at the April 2004 meeting of the Seismological Society of America (Veilleux, 2004). She is currently analyzing digital seismograms of recent (post-1988) Benioff zone earthquakes. Dr. Doser has completed relocation of Benioff zone events occurring between 1964 and 1988. She has also digitized waveforms of moderate (5.7 to 6.3) earthquakes occurring up to 15 years prior to the 1964 mainshock and begun analysis of these events. Mr. Steven Hoffmaster, an MS student in physics, has begun analysis of the intensity data.

A paper on changes of crustal seismic moment rates in the Anchorage region following the 1964 Great Alaska earthquake was published in the Bulletin of the Seismological Society of America in early 2004. This research has been conducted in collaboration with Dr. Natasha Ratchkovski (Alaska Earthquake Information Center), Dr. Peter Haeussler (USGS, Anchorage), and Dr. Richard Saltus (USGS, Golden). A paper on the crustal seismicity of the Anchorage region (Flores and Doser, 2004) has been submitted to the Bulletin of the Seismological Society of America. In February and March 2004 Dr. Doser visited with Dr. Haeussler and Dr.

Figure 1 - Map of Anchorage study area with locations of cross sections shown in Figures 3 through 6.



Ratchkovski in Alaska to discuss preliminary results of her research on crustal and Benioff zone earthquakes. Dr. Haeussler also visited El Paso in October 2004 to discuss ongoing research with Dr. Doser and Ms. Veilleux.

Results:

Task 1 (post-1964 relocations of Benioff zone events)

Figure 2 shows ~9800 earthquakes occurring between 1964 and 1999 at depths > 30 km that have been relocated using the HypoDD technique and phase data from the U.S. Geological Survey (USGS) and Alaska Earthquake Information Center (AEIC). Cross sections along the strike of the Benioff zone (Figure 3) and perpendicular to the strike of the Benioff zone (Figures 4 through 6) illustrate the complexities of subduction within this region. Earthquakes within 25 km of the cross section lines (Figure 2) have been projected onto the cross sections. Events of magnitude > 5.0 are indicated by solid stars.

Figure 2 shows major concentrations of seismicity at depths of 30 to 50 km north of Anchorage, east of Anchorage, and in the southwestern portion of the study area. Earthquakes occurring at depths of 50 to 90 km parallel the 50 km Benioff zone contour of Plafker et al. (1994) (dashed line, Figure 2) . The increase in seismicity north of Anchorage is likely related to a tear in the downgoing plate (Ratchkovski and Hansen, 2002). The concentration of seismicity in the southwestern portion of the study area occurs near the projected edge of the subducting Yakutat block. Note that the study area boundaries do not show the complete Benioff zone seismicity for events > 90 km depth.

Figure 3 indicates seismicity parallel to the strike of the Benioff zone (A-A', Figure 1). Intense seismicity at depths of 30 to 40 km is observed from 140 to 225 km along this cross section. Ratchkovski and Hansen (2002) suggest that the tear in the downgoing plate is located at ~ 220 km along this cross section. The concentration of seismicity observed at 50 km could be related to the southwestern edge of the Yakutat block.

Seismicity along a cross section taken near the tear in the downgoing plate (B-B', Figure 1) shows an abrupt increase at 120 km along the cross section (Figure 4). This seismicity extends from the lower plate into the upper plate and suggests strong coupling across the plate interface. Stress orientations of events in the upper (< 30 km) and lower (> 30 km) also suggest continuity in the direction of maximum compressive stress (Flores and Doser, 2004) across the plate interface. This zone of concentrated seismicity is the likely nucleation zone for the 1943 Mw=7.0 Susitna Lowlands earthquake (Flores and Doser, 2004).

A cross section of seismicity through upper Cook Inlet (C-C', Figure 2) indicates a thinner Benioff zone, although there is a concentration of events beneath Anchorage (Figure 5). In 2002 this region was the site of several M~5.0 events.

A cross section of seismicity in the southwestern portion of the study area (D-D', Figure 2) indicates an unusual concentration of seismicity beneath the main Benioff zone at depths of 60 to 70 km (Figure 6). This unusual cluster is not an artifact of the selected cross section strike. Three-dimensional views of the cluster suggest that it is ellipsoidal in shape.

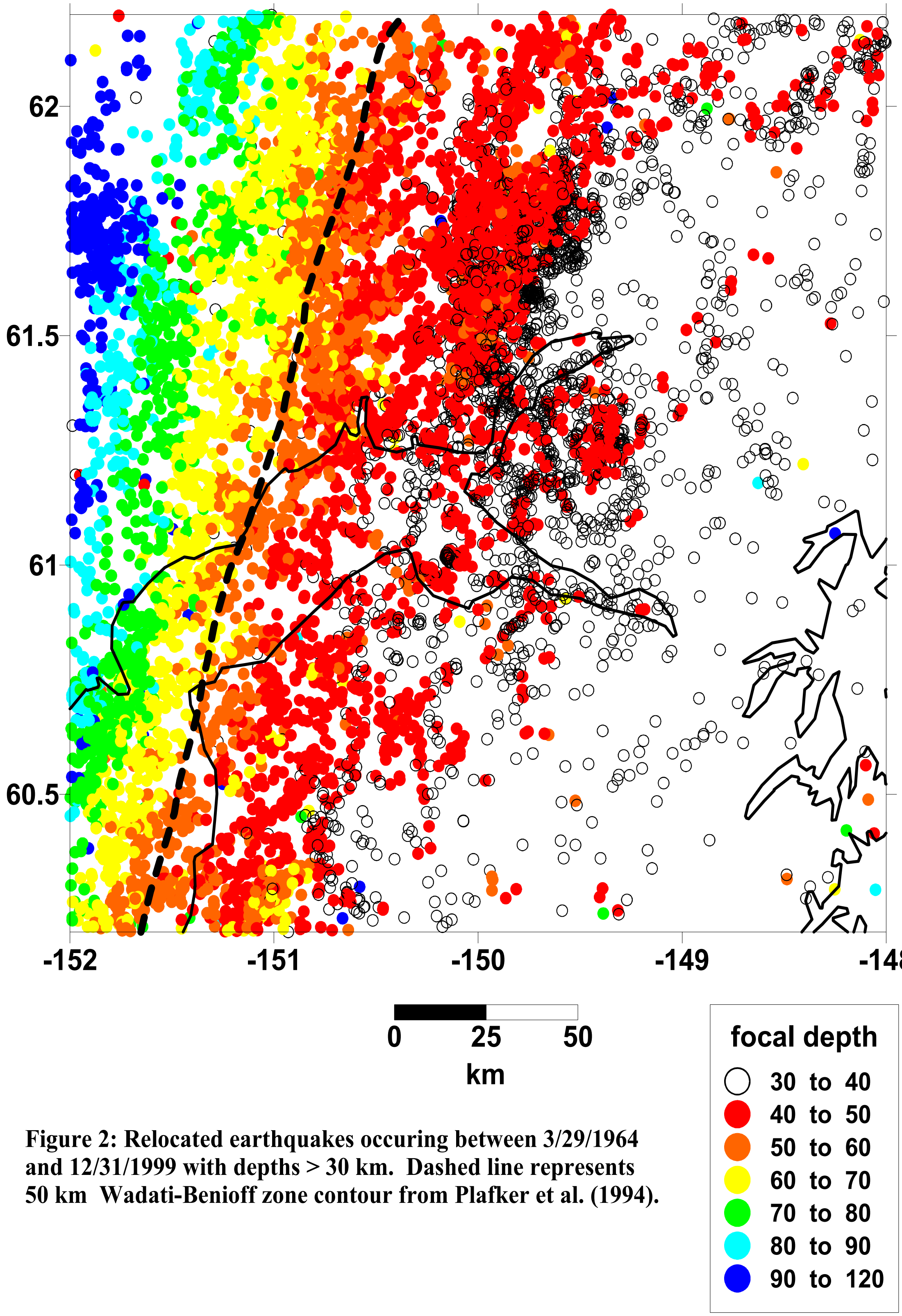


Figure 2: Relocated earthquakes occuring between 3/29/1964 and 12/31/1999 with depths > 30 km. Dashed line represents 50 km Wadati-Benioff zone contour from Plafker et al. (1994).

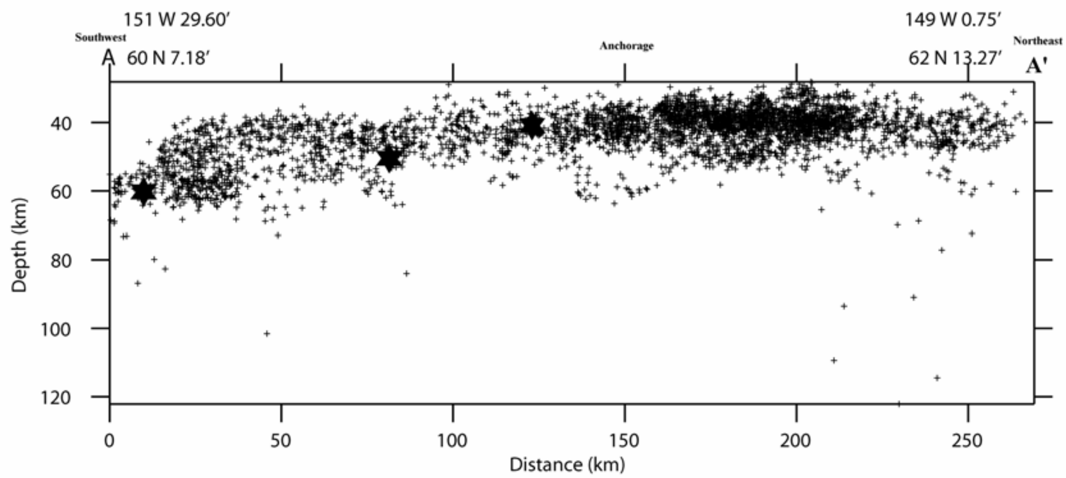


Figure 3 – Cross section along strike of the Benioff zone (A-A', Figure 1).

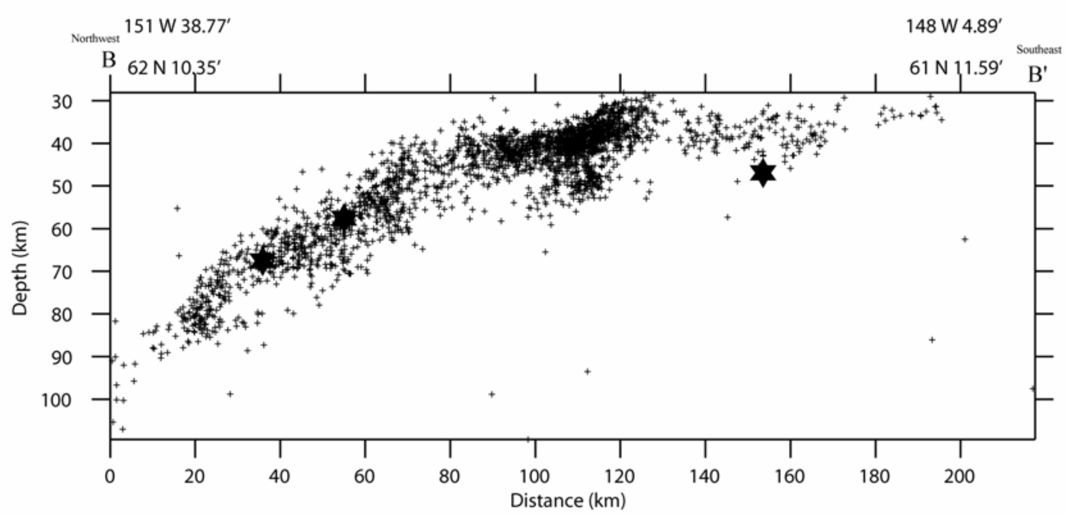


Figure 4 – Cross section along dip of Benioff zone near tear in downgoing plate (B-B', Figure 1).

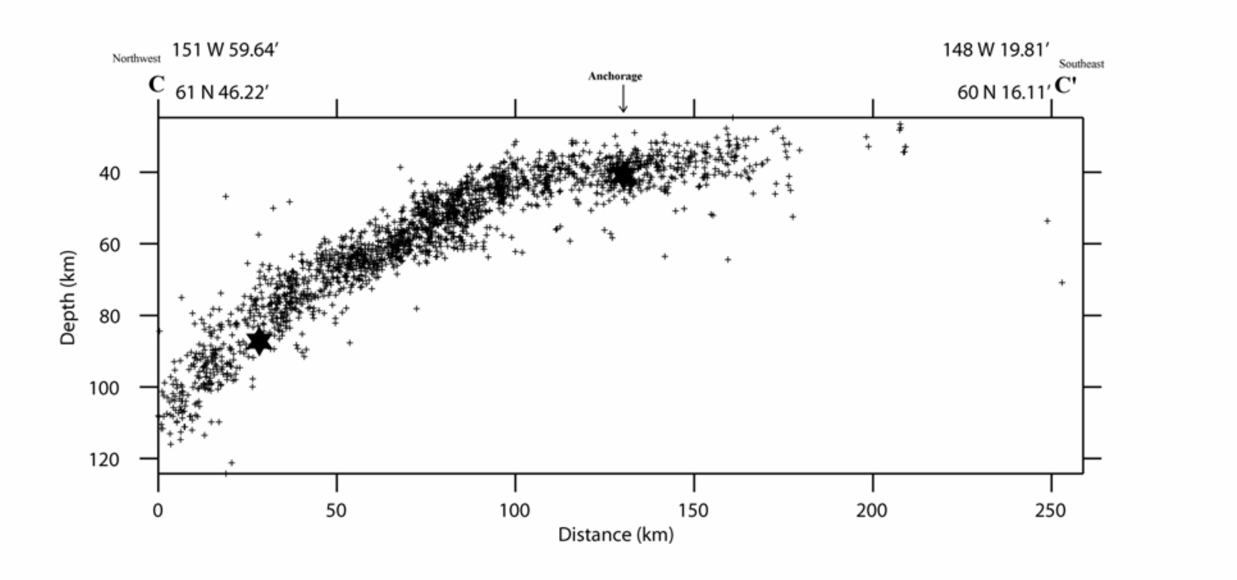


Figure 5 – Cross section along dip of Benioff zone in Upper Cook Inlet (C-C’, Figure 1)

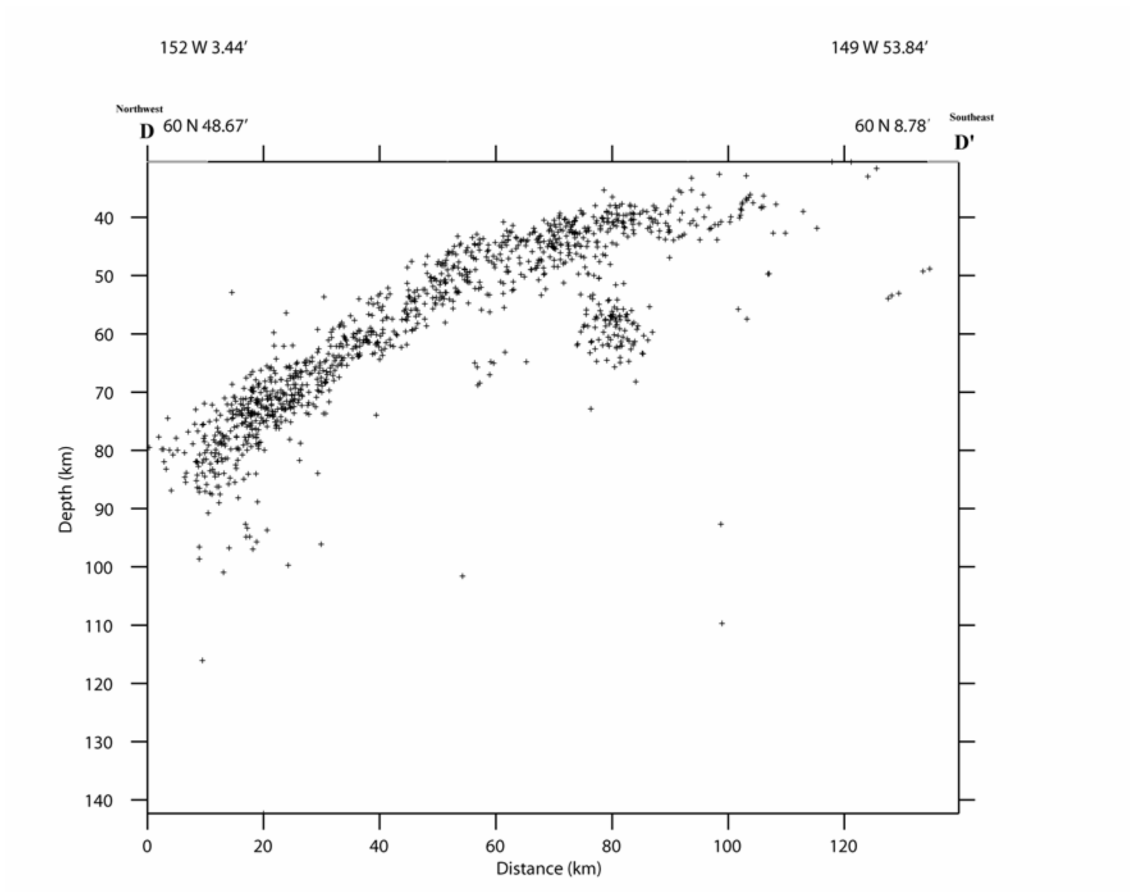


Figure 6 – Cross section along dip of Benioff zone in southwestern portion of study area (D-D’, Figure 1)

In addition to analysis of the spatial variation in seismicity within the study area, we have examined the temporal variations in seismicity. The only notable temporal variation we observed was at 30 to 40 km depth (Figure 7) where seismicity increased in the region east of Anchorage between 1983 and 1988 (red diamonds, Figure 7). The increase in seismicity may be related to two Mw>6.0 earthquakes occurring in the Columbia Bay region in July and September of 1983. Note that the region north of Anchorage has been continuously active throughout the time period we analyzed.

Task 2 (regional waveform modeling, post-1983 events)

We have collected digital waveform data for lower plate events (M≥5.0) shown in red in Figure 8. Note that many of the events within Upper Cook Inlet have similar hypocenters so that they can be used in empirical Greens function analysis studies. Figure 9 shows waveforms of two of these lower plate events. Ms. Veilleux is currently in the processing and modeling these waveforms.

Task 3 (teleseismic and regional waveform modeling of events occurring between 1950-1964)

We have digitized all waveforms for pre-1964 mainshock events of M≥5.0 and events occurring prior to the onset of digital recording (in ~1983) (blue diamonds, Figure 8). Note that many of the events occur either north or south of more recent earthquakes, which will hamper the use of the most recent events as empirical Greens functions for source parameter analysis of the older events.

Task 4 (analysis of intensity information)

We have collected intensity data for earthquakes occurring in the Anchorage region between 1964 and 1985 from the NOAA intensity web site. In addition, we have used zip code/internet response-based intensity information collected from the USGS's "Did You Feel It?" data archive (pasdena.wr.usgs.gov/shake/ak). Mr. Steven Hoffmaster has begun to develop an attenuation relationship for distance versus intensity. The pattern of the fall-off of intensity with distance is very similar for the 1964 mainshock, lower plate events in 1968 and July 1983 (Columbia Bay), and the 1984 crustal Sutton earthquake. All events have $M_w \geq 5.7$. In contrast, three Pacific Plate events with $M_w \leq 5.1$ show a different fall-off. Two of these events occurred nearly directly beneath Anchorage in 2002 so that intensity variations may have been strongly controlled by near site effects, since many sites were nearly equidistant from the earthquakes. The other event was a 90 km deep event in March 1978 located on the western side of Cook Inlet. This location could skew intensity observations, since few people live west of the Inlet. However, an event in December 1968 event also occurred west of Cook Inlet at a depth of 86 km and appears to follow the fall-off pattern of other $M_w>5.1$ events. This suggests that the steeper fall-off for March 1978 may be controlled more by its lower magnitude. The September 1983 Columbia Bay event (M_w=6.4) exhibits a fall-off in intensity that appears to mix aspects of the two dominant fall-off patterns. This event occurred very close to the hypocenter of the July 1983 event, but had a slightly different focal mechanism.

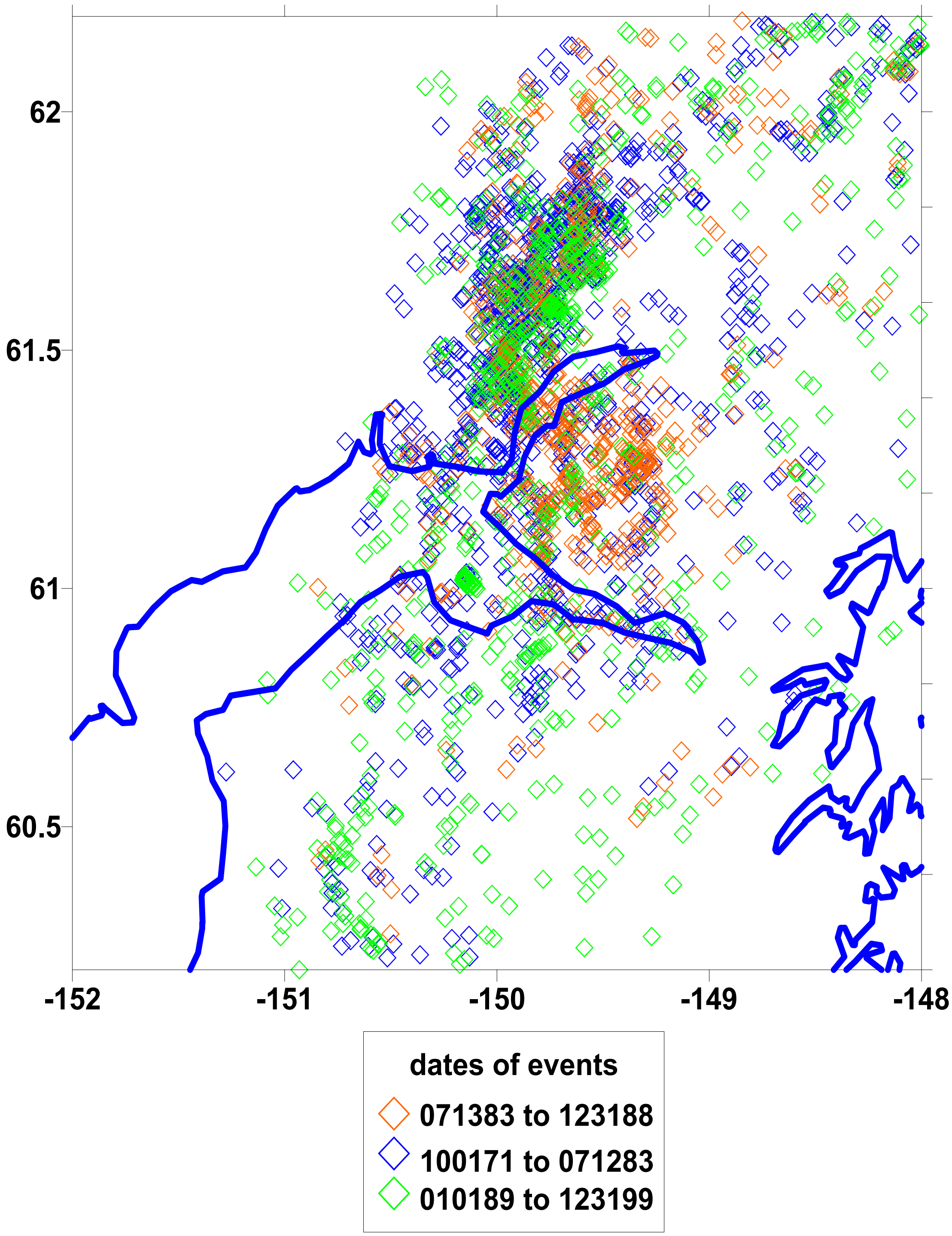


Figure 7 - Temporal variation in seismicity in study area at depth of 30 to 40 km.

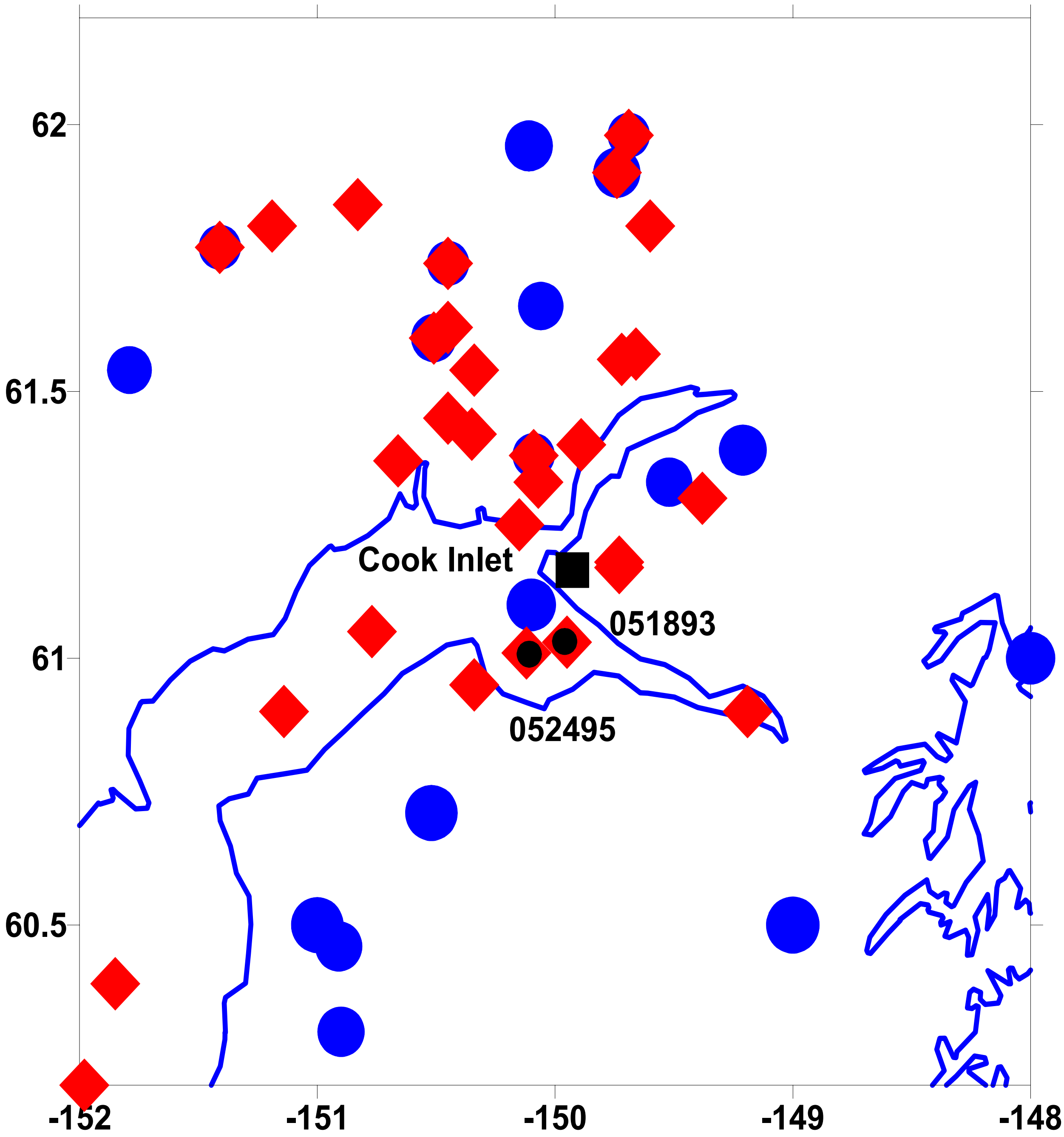


Figure 8 - M>=5.0 events for waveform modeling studies. Red symbols are post-1982 events, blue symbols are pre-1983 events. Event size is scaled to magnitude. Black square indicates Anchorage. Black dots indicate events whose waveforms are shown in Figure 9.

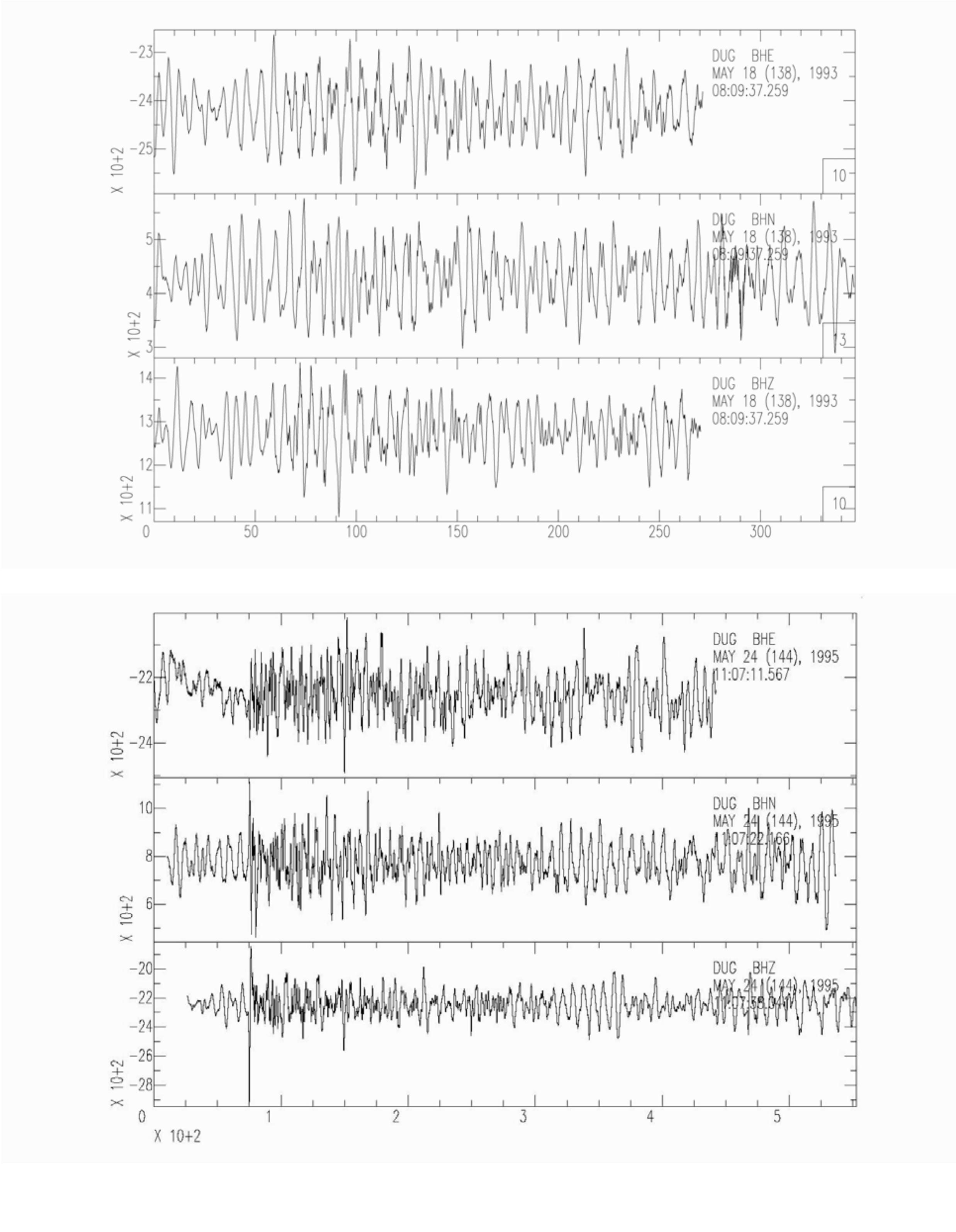


Figure 9 – Examples of unfiltered digital waveforms of the May 18, 1993 (top) and May 24, 1995 earthquakes (see map, Figure 8, for location) recorded at Dugway, Utah.

These preliminary results suggest that events of $M_w \geq 5.7$, regardless of position (crust, interface, subducted slab), may create similar amounts of shaking. This could make it difficult to use intensity information from historical events to help estimate event focal depth. The 2002 events may also serve as a good model for intensity fall-off for larger events occurring directly beneath Anchorage. We have also collected intensity data for events in the Alaska interior, Kodiak Island region, and southeastern Alaska with the hope we will be able to compare intensity fall-off between regions.

Related Studies

In addition to progress toward our four tasks outlined above, we have conducted studies of seismic moment rates in the Anchorage region and have studied the crustal seismicity of the Denali fault zone (1912-1988). Our seismic moment rate calculations show a factor of 1000 decrease in moment rates following the 1964 mainshock. We then used geologic information on structures within Cook Inlet basin (e.g. Haeussler et al., 2000) to estimate a regional geologic moment rate. Since it is difficult to estimate the amount of horizontal offset that has occurred along these structures, our geologic moment rates could underestimate the true rates by up to 70%. Nevertheless, the geologic moment rate is only 4 to 10 times lower than the pre-1964 mainshock seismic moment rate. This suggests that the 1964 mainshock has significantly slowed regional crustal deformation. If we compare the geologic moment rate to the post-1964 mainshock rate, the moment rate deficit over the past 36 years is equivalent to a Mw 6.5 to 6.8 earthquake. This highlights the difficulty in using seismicity in the decades following a large megathrust earthquake to adequately characterize long-term crustal deformation. These results were published in the Bulletin of the Seismological Society of America (Doser et al., 2004).

A paper on historical seismicity of the Denali fault zone is in press for a special issue of the Bulletin of the Seismological Society of America (Doser, 2004a). The paper concentrates on seismicity prior to 1971, although earthquakes occurring between 1971 and 1998 were relocated. In addition to the relocations, waveform modeling for events of M>6.0 were conducted. The waveform modeling and earthquake locations suggest that most M>6.0 events occurred on strike-slip or reverse faults located either south or north of the Denali fault. A magnitude 6.5 event in 1929 appears to have occurred within the subducting slab at a depth of ~ 60 km. Events in 1962 appear to have occurred upon a reverse fault that may be the extension of the Pass Creek fault. A magnitude 6.9 event in 1932 appears to be a deeper event (~30-40 km) along a left-lateral strike-slip fault. Of considerable interest is the July 7, 1912 earthquake (M~7.2). This has been relocated to the vicinity of the Denali fault, although its 95% confidence ellipse is very large. Surface wave and body wave amplitudes observed for two stations (Riverview, Australia and Honolulu, Hawaii) are not inconsistent with rupture along the Denali fault. If the 1912 event actually occurred on the Denali fault, this may explain why the portion of the Denali fault located between the October 2002 Nenana Mountain rupture zone and the November 2002 Denali rupture zone was relatively aseismic during the 2002 sequence.

A paper on the crustal seismicity (< 40 km depth) of the Anchorage study area was submitted to the Bulletin of the Seismological Society of America in July 2004 (Flores and Doser, 2004). We have relocated over 4200 shallow (≤ 40 km) earthquakes occurring in the Anchorage region for ~35 years following the 1964 great Alaska earthquake. The shallowest (< 20 km) earthquakes delineate several faults within the crust, including one associated with mapped folds located north of Upper Cook Inlet. Inversion of first motion data for the stress field orientation in Upper Cook Inlet indicates east-west oriented horizontal σ_1 and near vertical

σ_3, a condition favoring reverse faulting along east-west striking faults with trends similar to the orientation of mapped faults and fault cored anticlines within the inlet. σ_1 is rotated 60° to 90° counterclockwise from the direction of plate convergence, in agreement with GPS/geodesy studies that indicate the western portion of the Kenai Peninsula and upper Cook Inlet do not appear to be moving in the direction plate motion due to a change in coupling across the plate interface. The stress regime north of the Castle Mountain fault is conducive to strike-slip or normal faulting along faults striking east-northeast or north-northwest. Similar to previous studies we observed a persistent zone of seismic quiescence in the upper crust that appears to be located above and immediately downdip of the portion of the plate interface that slipped 20-25 m in the 1964 mainshock. Deeper (20 to 40 km) earthquakes indicate intense deformation and a rapidly changing stress field near the boundary between the Kenai and McKinley segments of the subducted slab. The 1943 M_w=7.0 Susitna lowlands earthquake may have been associated with this region of complex deformation.

A paper on the historical seismicity of the Kodiak Island region was also submitted to the Bulletin of the Seismological Society of America in August 2004 (Doser, 2004b). This paper has been accepted for publication pending minor revisions. Thirty-five earthquakes were relocated and waveform modeling studies of 12 events were conducted. The events were located primarily within the Kodiak portion of the 1964 great Alaska earthquake rupture zone and the northeasternmost portion of the 1938 Semidi earthquake rupture zone. These results show that there is considerable similarity between pre-1964 mainshock seismicity and post-1964 mainshock seismicity. Persistent seismicity has occurred for the past ~85 years at the southwestern end of the 1964 rupture zone, a region where GPS/geodesy studies indicate the plate interface is currently locked. Earthquakes also occurred frequently within the Kennedy Entrance region where the transition between the Kodiak and Kenai block of the subducting Pacific plate occurs. The seismic moment rate for post-1964 mainshock seismicity is about 2 times larger than for pre-mainshock seismicity. This is in contrast to the Prince William Sound portion of the 1964 rupture zone where post-1964 mainshock moment rates are orders of magnitude lower than pre-1964 mainshock rates and the pattern of seismicity has changed considerably with time. These observations reinforce previous studies that indicate the behavior of plate subduction beneath the Kodiak Island region is much different that that beneath the Prince William Sound region.

Finally, we have begun to collect waveform and phase data for the southern Kenai Peninsula/Prince William Sound region for analysis similar to that we have conducted for the Anchorage region. These data will be used in a funded NEHRP project that will begin in 2005. Mr. Alejandro de la Peña, an MS student in geophysics, has begun work on this project.

Non-technical Summary:

This study focuses on earthquake hazards of the Anchorage, Alaska region. Major tasks in the study are to relocate and merge hypocentral data for the 1950-2001 time period in order to examine the nature of deeper Pacific plate earthquake source zones near Anchorage and model seismic waveforms to better understand seismic sources within the Pacific plate. We will also compile intensity information for earthquakes in the region, which will provide insight into variations in ground shaking and their relationship to local geologic conditions.

Reports Published:

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94, 320-325, 2004.

Doser, D.I., Seismicity of the Denali-Totschunda Fault Zone in Central Alaska (1912-1988) and its Relation to the 2002 Denali Fault Earthquake Sequence, in press, Bull. Seismol. Soc. Amer., 2004a.

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Veilleux, A.M., and D.I. Doser, A study of Benioff zone seismicity (1964-1999) in the Anchorage region, Alaska, Seismol. Res. Lett. 75, 274, 2004.

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Haeussler, P.J., R. L. Bruhn, and T.L. Pratt (2000). Potential seismic hazards and tectonics of Upper Cook Inlet Basin, Alaska, based on Pliocene and younger deformation, *Geol. Soc. Am. Bull.* **112**, 1414-1429.

Plafker, G., L.M. Gilpin, and J. C. Lahr (1994). Neotectonic map of Alaska, *in The Geology of North America*, **vol. G-1**, The geology of Alaska (G. Plafker and H.C. Berg, eds.), Geol. Soc. Amer., Boulder, Colo., pp. 389-449.

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Waldhauser, F., and W.L. Ellsworth (2000). A Double-Difference earthquake location algorithm: method and application to the northern Hayward fault, California, *Bull. Seismol. Soc. Am*. **90**, 1353-1368.

Availability of Data Sets:

Copies of phase data and intensity data that are being used in the analysis will be available in paper or digital form. First motion data and waveform data are also available in digital form. Contact the principal investigator, Dr. Diane Doser, for more details at (915)-747-5851 or doser@geo.utep.edu.